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PRINCIPLES OF PLANT HEALTH MANAGEMENT FOR ORNAMENTAL PLANTS

Margery L. Daughtrey[1] and D. Michael Benson[2]
[1]Department of Plant Pathology, Cornell University, Long Island Horticultural Research & Extension Center, Riverhead, New York 11901; email: mld9@cornell.edu
[2]Department of Plant Pathology, North Carolina State University, Raleigh, North Carolina 27695-7629; email: mike_benson@ncsu.edu

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■ **Abstract** Economic, environmental, and technological influences complicate the task of achieving disease-free products in the ornamentals industry. Integrated pest management (IPM) is a cornerstone of floriculture and nursery crop production: strategies include sanitation, clean stock, host resistance, and control through biological, cultural, environmental, chemical, and regulatory means. Sanitation measures and cultural controls must keep pace with new production technologies. Clean stock programs are used for many crops that are propagated vegetatively. Breeding, selection, and biotechnology provide crops resistant to pathogens. Offshore production for economic competitiveness can introduce pathogens that make regulatory programs necessary. New biocontrol and chemical products continue to improve control while meeting the requirement for minimal environmental impact. Continual introduction of new crops and new production technologies creates new opportunities for pathogens to exploit, such that new disease management tactics must be discovered and old ones rediscovered to achieve optimum health management for ornamentals.

INTRODUCTION

The unique features of the pathology of ornamental plants were reviewed by Baker & Linderman 25 years ago (7). They described how flare-ups of diseases such as Verticillium wilt and chrysanthemum stunt in chrysanthemum, Cylindrocladium wilt in azaleas, rose mosaic, and bacterial blight of geraniums precipitated major improvements in sanitation and indexing procedures that ultimately secured profitability of the crops.

Since 1979, the ornamentals industry has continued to be rocked by disease outbreaks. In the greenhouse industry, bacterial blight of geraniums caused by *Xanthomonas campestris* pv. *pelargonii*, *Impatiens necrotic spot* (INSV) and *Tomato spotted wilt* (TSWV) tospoviruses, and the bacterial wilt caused by *Ralstonia solanacearum* race 3, biovar 2 have had the most impact. In the nursery industry, the effect of sudden oak death caused by *Phytophthora ramorum* has far outweighed that of any disease to date. These, along with thousands of other host-pathogen interactions, make up the contagious disease challenges of plant health management for growers of ornamentals.

Cline et al. described research needs in ornamentals pathology in 1988 (35), many of which are still relevant. Despite significant progress to date, the constant change in crops and systems requires continuing investment in both research and extension specific to the health management of greenhouse- and nursery-grown ornamentals. As we review research findings that relate to the principles of plant health management for ornamentals, our discussion will of necessity show a largely U.S. perspective, but with full realization that both research and production in the United States are intricately linked to parallel endeavors around the globe.

The Value of the Industry

Production of ornamentals in the United States is an increasingly important agricultural enterprise. The position of the ornamentals industry is much less institutionalized than the rest of agricultural production: although subject to many of the same problems, ornamentals growers do not enjoy the same governmental subsidies or a proportionate quantity of public funding for research.

Although concerned with minor crops, the industry has a very substantial collective value. Cash receipts of the floriculture and nursery industries combined were estimated at $14.3 billion in 2003, making them the fourth largest crop group in the United States (159). Offshore production continues to compete for the U.S. market: imports of cut flowers and nursery stock have reached $1.2 billion.

FLORICULTURE INDUSTRY For the floriculture segment alone, the estimated wholesale value in 2003 was $5.07 billion in the 36 primary production states (159). The top four floriculture production states in terms of sales dollars were California (19.8%), Florida (16.2%), Michigan (6.7%), and Texas (5.8%). Thirty-nine percent of the growers in the survey had at least $100,000 in sales, and these larger growers accounted for 93.9% of all sales. The floriculture industry encompasses producers of bedding/garden plants, prefinished/propagative materials, foliage plants, cut flowers, potted flowering plants, and cut cultivated greens. Of these, the bedding plant segment (including herbaceous perennials as well as annuals) is clearly dominant, accounting for 55% of the industry.

NURSERY INDUSTRY The estimated wholesale value of nursery crops was $9.16 billion in 2003 (159), with 49 states reporting. States in the South and West accounted for 45% and 31%, respectively, of total production. California (14%), Texas (12%), Oregon (9%), North Carolina (8.5%), and Florida (8.5%) accounted for 52% of total production. Nursery crops are sold as container grown or dug from the ground (balled and burlapped, or bare root) and include shrubs, trees, and perennials broadly classed as broadleaf evergreens, coniferous evergreens, deciduous shade trees, deciduous flowering trees, deciduous shrubs, vines, and groundcovers.

Nature of the Industry

No other type of agriculture embraces as many different families, species, and cultivars of plant species. Baker & Linderman (7) estimated that 1100 genera of plants were grown as ornamentals in 1979, and this number has only increased. The industry is "plagued by. . . transitory varieties" (7), as plant breeders continually introduce lines with new, appealing foliage and/or flowering characteristics. Mixed-species culture is typical and this complicates all cultural decisions, including those related to plant health. Crops are annual or perennial, both herbaceous and woody; they may be produced from seed or (increasingly) by vegetative propagation (so that desirable traits may be quickly capitalized upon for sales of "new or improved" plants).

The ornamentals industry in the United States uses diverse crop production methods. Plants are produced in fields, outdoor shaded/open container areas, and greenhouses. Field production is more concentrated in the southern states. Outdoor production is in fields or beds, in containers that are on ground cloth or gravel surfaces, or set into pots recessed into the ground (pot-in-pot system). Greenhouses may be of glass or fiberglass, or more commonly, are covered with poly film. Irrigation methods include overhead, drip tape, trickle tubes, capillary mats, ebb/flood benches or troughs, flood floors, and flood trays.

Influences on the Ornamentals Industry

GLOBALIZATION The seed and cuttings used for propagation of ornamentals may originate thousands of miles from where the plants are finished and sold. Increasingly, offshore sites are utilized for the production of cuttings, because of the availability of high light and lower heating and labor costs. Globalization is bringing host plants in U.S. production into contact with new pathogens, notably *Ralstonia solanacearum* race 3, biovar 2 on geraniums (170), powdery mildew on poinsettias (42), and *Phytophthora ramorum* on multiple woody hosts (132, 155).

ENVIRONMENTAL CONCERN Environmental regulations and water restrictions in the United States are at times very limiting to the producers and consumers of ornamentals. Plant health concerns must be addressed without compromising the environmental health of the adjacent areas. At all phases of plant production, there is a need for inexpensive, effective, and nonpolluting disease management. It is the strong public demand for environmentally benign plant production that has most changed the tenor of plant disease management in the past 25 years.

NEW TECHNOLOGY Technology is a major driving force in the changing face of floriculture and nursery crop production. New technology—much of it computer-controlled—and the economies of large-scale production have been adopted by some growers to save labor costs; however, new disease problems can develop as a result. Automated plug tray devices can remove medium from plant-less cells in a tray and replace with new seedlings, but if the medium removed was infested with a pathogen such as *Thielaviopsis basicola* the new seedling may become diseased (162). Irrigation by floor flood or ebb and flood is popular for some potted plants. However, recycling irrigation water can be contaminated with pathogens such as *Pythium* spp., resulting in disease outbreaks (136).

PLANT HEALTH MANAGEMENT: PRINCIPLES

Plant health management is a primary concern for producers of ornamentals. The entire plant is harvested and marketed in most cases, so that price and saleability are directly related to the attractiveness of flowers, stems, and leaves. Ornamental businesses are profitable enterprises only if the plants are carefully guarded against any injury.

Plant health management programs for ornamentals, as for other crops, must ensure the health of the plant material entering production, provide cultural conditions that work against disease development, and make arrangements to correctly identify and treat problems that do arise. The integration of these principles is the secret of effective management.

This review covers the advancements in scientific knowledge of plant health management for ornamentals that relate to the key principles of sanitation, clean stock, regulatory actions, host resistance, environmental control, cultural control, biocontrol, chemical control, and disease diagnosis.

Sanitation

Sanitation practices are one of the surest control measures available to a grower. As mentioned below under "Cultural Control," extensive adoption of soilless medium has eliminated many disease problems caused by soilborne plant pathogens in ornamentals production. Soil is still occasionally used as a potting mix component, however, or in ground beds. The accepted treatment for freeing soil from pathogens since the mid-1960s has been the use of aerated steam for pasteurization (2, 3, 46), which leaves some beneficial microorganisms in the soil rather than creating a biological vacuum. Structural solarization recently has been developed for greenhouses (143).

Methyl bromide has been used for soil disinfestation by woody plant propagators and cut flower growers in particular for many years (32). Methyl bromide and alternative fumigants and their use with soil solarization are discussed by Tjamos et al. (154). Methyl bromide is, however, scheduled for discontinuation of both manufacture and use in developed nations by 2005, according to the Montreal Protocol.

Greenhouse culture is somewhat protected from external environmental contamination, but doorways and vents are entry points for pathogens. Positive pressure air flow is sometimes used to minimize entry of airborne propagules, and footbaths are filled with disinfectant at entrances to reduce soil entry (19). Soil particles in the greenhouse moved by grower activity may be a source of *Pythium* or *Rhizoctonia* (152). Use of screening materials to exclude Western flower thrips vectors from entering greenhouses through vents and doorways is integral to control of INSV (11). Water used for irrigation can also be a source of pathogens, or can provide a medium by which pathogens introduced on plants are recirculated; the technology for water disinfestation by physical, chemical, and biological means is critically important for greenhouses and nurseries using recirculating irrigation (51, 134).

Floriculture crops themselves tend to become sources of inoculum in the greenhouse over time. Sporulation of *Botrytis cinerea* on dead leaves at the base of geranium stock plants (70, 71) and on dead gerbera tissue (88) that accumulates as a crop ages leads to inoculum for cutting wound and flower infection as well as postharvest flower spotting. Keeping plant debris in covered containers and clearing overmature, unsold plants from the greenhouse promptly are advisable (69).

Crop sanitation includes control of weeds that are pathogen reservoirs as well as control of arthropods that vector pathogens. Management of weed reservoirs and the thrips vector is essential to avoid losses from TSWV or INSV (44). Aphids, whiteflies, shore flies, and fungus gnats commonly vector various plant pathogens in greenhouses and nurseries (45).

Clean Stock

A key aspect of plant health management is starting with clean propagative material. Most ornamentals are multiplied via vegetative propagation, so there is a greater danger of pathogen passage than in seed-propagated crops. The bedding plant industry today increasingly uses vegetative propagation for the production of new annuals so that new lines can be introduced more quickly. This propagation is often conducted offshore; unrooted cuttings taken from "mother plants" are then shipped into U.S. "rooting stations" before dissemination to growers. Certification programs for ornamentals have been voluntarily undertaken by the industry until quite recently. Concerns over the introduction of *R. solanacearum* race 3 biovar 2 into the United States have led to a U.S. Department of Agriculture (USDA)-Animal and Plant Health Inspection Service (APHIS) certification program for geraniums grown offshore (see Regulatory Actions section).

CULTURE INDEXING In the mid-twentieth century, systemic diseases were a major limiting factor in the production of some of the more traditional floral crops. Technology was developed to insure a clean start through culture indexing to remove bacterial and fungal contaminants, and through heat treatment to eliminate viruses prior to meristem tip culture (128). Indexing programs systematically detect and dispose of potential propagation material contaminated with a pathogen, to ensure that only healthy plant material is used for production. Klopmeyer (91) outlined four key principles to guard the health and quality of vegetatively propagated geraniums: annual renewal, unidirectional flow, repeated testing, and clonal selection. The first culture-indexing procedure was used to eliminate *Verticillium* from chrysanthemums (48) and similar methods were later applied to geraniums (120) to eliminate *Verticillium* as well as *X. campestris* pv. *pelargonii.*

VIRUS INDEXING Virus- and viroid-indexing procedures have evolved over time. Traditional bioassays using inoculation or grafting to indicator plants still have some utility, but have largely been abandoned in favor of faster methods (91). A serological method, enzyme-linked immunosorbent assay (ELISA) has now become standard for virus testing. Lawson described the development of indexing techniques for a wide variety of bulbs as well as other flower crops (99). Newer molecular techniques (28, 100, 137) are gaining popularity. If viral contamination is detected, then various techniques may be employed to free the plant material of the virus or viruses (79, 119). For geraniums, heat therapy is best accomplished by a program that uses gradually increasing temperatures until a final 38°C day, 33°C night is reached and maintained for 3–4 weeks (91). Subsequent meristem tip culture allows development of young plants that can be virus-indexed. A modification of these procedures is used to verify the health of micropropagated plant material. Indexing programs are used for a number of floriculture crops today, including foliage plants, Easter lilies, Asiatic lilies, iris, gladiolus, chrysanthemum, carnation, New Guinea impatiens, and geranium (91).

Seed Treatment

Pathogens may be associated with seeds in three basic ways, which determine what treatments are effective to free the seed from contamination (5). Pathogens can be mere accompaniments of seed (e.g., the seeds of the parasitic plant *Cuscuta* spp., sclerotia of *Sclerotinia*, or contaminated bits of plant tissue as with *Puccinia malvacearum*, hollyhock rust); attached exterior contaminants, e.g., *Puccinia antirrhini* on seed of snapdragon, *Antirrhinum majus*, and *Rhodococcus* (*Corynebacterium*) *fascians* on nasturtium and sweet pea; or they may be internal. Internal contamination results when the pathogen has entered via flower parts, such as *Alternaria zinniae* on zinnia; penetrated through the vascular system, such as *Fusarium oxysporum* f. sp. *mathiolae* causing Fusarium wilt of *Mathiola*; or has infected the seed directly, such as *Heterosporium tropeoli* causing heterosporium disease of nasturtium (5). Some viruses, also, may be carried in or on seed.

Sunflower seeds that are infected with the downy mildew *Plasmopara halstedii* will produce systemically infected plants (50). Oospores of *Plasmopara obducens*, the downy mildew of impatiens, have been observed in seed of balsam impatiens, and were demonstrated to lead to disease when infested seed was planted into sterile soil (151).

Fungicide treatments in the field should be carefully plotted according to the specific diseases potentially seed transmissible for each crop. Use of benzimidazole fungicides has been associated with increased *Alternaria* recovery from seed (145), for example, and this practice would thus be inappropriate during field production of seed for flowers such as zinnia that are susceptible to Alternaria diseases. Currently, thiram is the only fungicide labeled for postharvest treatment of flower seeds in the United States. Thiram gave an 80% reduction in seedborne anthracnose in the field crop *Lupinus albus*, a relative of the ornamental lupine (153).

The postharvest treatments of seed potentially include biological, physical, mechanical, and chemical methods. Such a high value is placed upon germination percentage in plug trays of bedding plants that tolerance for any phytotoxic effects on seed germination is very low. Consequently, there has as yet been little utilization of seed treatments to eliminate bacterial, fungal, or viral agents in ornamentals, but information is available (131).

Thermotherapy is sometimes employed to free plant propagules from pathogens (59). Hot water can be used for pathogen eradication from corms, bulbs, tubers, and seeds, and has the advantage of penetrating to internally harbored pathogens. Aerated steam (4) used at 56°–57°C for 30 min is safer than hot water and more effective than hot air for seed treatment, especially if seed moisture content is increased before treatment. Although short-term exposure to high temperature will often free seeds from bacteria and fungi, generally longer periods of exposure (one to several days) are more effective for eliminating viruses (1). Because there is a risk of reduced germination percentage with any heat treatment, this approach is not widely used by the flower seed industry.

Seed health testing must be carried out to insure freedom from pathogens of concern. Neergaard gives test procedures applicable to many pathogens of flower crops (116).

Regulatory Action

For some ornamental pathogens, notably *P. ramorum* and *R. solanacearum* race 3 biovar 2, regulatory actions have recently been put in place by the USDA-APHIS, Plant Protection and Quarantine (PPQ). The purpose of the actions has been to protect American forests, landscapes, and agriculture from the diseases that these pathogens cause (74, 157).

Use of regulatory actions as a means of managing ornamental diseases goes well beyond simply putting in force a regulatory rule barring the introduction of infected plants. Regulatory scientists develop an action plan based on pathways of host movement in the ornamentals industry, on the epidemiology, ecology, and biology of the pathogen, and on cultural practices used for the ornamental crop.

CASE STUDY 1: *PHYTOPHTHORA RAMORUM* Sometime in the early 1990s, a disease of unknown etiology known as Sudden Oak Death began devastating coast live oaks and tanoaks in the coastal region of Northern California, centering on Marin County. In the late 1990s Rizzo & Garbelotto (132) isolated an unknown *Phytophthora* sp. from dying oaks that was later described as compatibility type A2 of *P. ramorum* (164). At the same time compatibility type A1 became recognized in Europe primarily as a pathogen of nursery plants including rhododendron and other ornamentals (83, 98, 164, 177). APHIS PPQ imposed a federal quarantine for 14 coastal counties in Northern California to limit the spread of this introduced, limited-distribution pathogen in the United States (157). A federal action plan (158) was put in place for nurseries in the quarantine area to insure that only disease-free plants were shipped.

In 2004, a large southern California nursery well outside the quarantine area unknowingly shipped infected camellias to 160 locations in 21 states, many of these in the eastern United States where there is great concern that red oaks (*Quercus falcata* and *Q. rubra*), dominant forest trees, will suffer the same fate as coast live oaks and tanoaks in California should *P. ramorum* be introduced. The occurrence of *P. ramorum* in the hot, dry climate of a southern California nursery was unexpected and points out the fact that nursery growing conditions with daily irrigation and shade can create a microclimate favoring *P. ramorum*.

Unfortunately, our current understanding of the biology and epidemiology of *P. ramorum* on nursery crops has gaps that could represent weak links in the regulatory plan. For instance, the role of chlamydospores in survival and infection may be important (101, 142) but the regulatory plan has no measures to prevent movement of soilborne inoculum on asymptomatic plants.

Although the regulatory action for *P. ramorum* has the potential to limit the distribution of the pathogen, it also has led to uncertainty among nurserymen and put the nursery industry at risk. Standard operating procedures at nurseries must be rethought to prevent the introduction of potentially infected plants. Integrated pest management (IPM) programs must include an emphasis on sanitation and cultural practices to avoid Phytophthora infection, and new strategies for nursery layouts are needed to avoid catastrophic loss through regulatory action, should the pathogen be inadvertently introduced. Compliance with regulations has become a new economic burden, and the reputation of the nursery industry in states where the disease has been detected is questioned, threatening future sales.

CASE STUDY 2: *RALSTONIA SOLANACEARUM* RACE 3 BIOVAR 2 In the case of *R. solanacearum* race 3 biovar 2, the perceived threat is to the U.S. potato crop, not necessarily to the geranium industry through which the pathogen has recently been introduced (170). *R. solanacearum* race 3 biovar 2 is on the USDA Agricultural Bioterrorism Act of 2002 Select Agents and Toxins list because of the potential threat, but the introduction of this pathogen on geranium has been determined to be inadvertent (157). Although southern bacterial wilt in geranium caused by *R. solanacearum* (now known to be race 1) is endemic in the southern United States, race 3 biovar 2 from the highland tropics of Africa and South America is adapted to cooler climates—thus the fear that eventually this race could infest the seed potato-growing region in North America if it were introduced (170).

In 2003 from Kenya and again in 2004 from Guatemala, countries where race 3 biovar 2 is endemic, a few infected geranium cuttings were introduced to U.S. rooting stations. The rooting stations inadvertently distributed infected geraniums to wholesale producers in a number of states. In a trace-forward effort, APHIS and the state departments of agriculture were able to identify the wholesale growers who received these plants and to destroy the infected plants. This caused great financial loss to the growers, as no reimbursement plan was in effect. Early detection and a rigorous trace forward effort were the key steps for finding and eliminating infected geraniums from U.S. wholesale producers before these plants were sold and planted in the landscape.

Host Resistance

Development of transgenic crops holds promise in floriculture, as a large number of cut flower crops have been transformed including rose, chrysanthemum, and carnation (133). The technical difficulty of developing transgenic plants in ornamentals is the lack of suitable transformation systems. However, regeneration of chrysanthemum has led successfully to transformation of the cultivar ‘Polaris’ with resistance to TSWV by insertion of a portion of the nucleocapsid gene (140, 141). Rose plants transformed with the antimicrobial protein gene, Ace-AMP1, were more resistant to *Sphaerotheca pannosa*, cause of powdery mildew, than were nontransformed plants (102). Insertion of the chitinase transgene in rose resulted in plants more resistant to *Diplocarpon rosae*, cause of black spot disease (105). The economic constraints for transforming a large number of cultivars of a given crop and the low rate of transformation may limit the commercial use of genetically transformed ornamental crops for disease management in the near future.

Selection of species and cultivars with natural genetic resistance to root rot has identified a number of resistant woody ornamentals. Rhododendron and azalea cultivars resistant to Phytophthora root rot caused by *Phytophthora cinnamomi* have been identified through screening programs (18, 77). A number of woody ornamentals with resistance to root-knot nematode (*Meloidogyne* spp), lesion nematode (*Pratylenchus vulnus*), ring nematode (*Macroposthonia xenoplax*), and stunt nematode (*Tylenchorhynchus claytoni*) were identified (15, 166).

Selection for resistance to foliar pathogens has been equally successful. The National Crabapple Introduction Program identified cultivars and species with resistance to apple scab (*Venturia inaequalis*), fireblight (*Erwinia amylovora*), rust (*Gymnosporangium* spp.), and powdery mildew that had good horticultural characteristics (14, 34, 65, 148). Active breeding and selection programs for disease resistance in ornamentals continue across government, university, and private sectors. The U.S. National Arboretum has released improved crapemyrtle cultivars with resistance to powdery mildew, and efforts continue on development of disease resistance in other crops. In university programs, resistant cultivars and species have been identified for major foliar pathogens in a number of woody ornamentals, as reported in *Biological and Cultural Tests for the Control of Plant Diseases* (*B&C Tests*).

Growers are slow to adopt host resistance as a strategy for IPM in commercial production unless a disease is so severe and other management tools so ineffective that production is threatened. As consumers become better educated about growing plants that are disease resistant and thus require less maintenance, demand for production of disease-resistant cultivars in floriculture and nursery crops will increase.

Environmental Control

The primary aim of environmental control of disease in a greenhouse is to restrict water availability to the pathogens, as bacteria and fungi need moisture in order to infect. Computer controls are used to make automatic adjustments in ventilation or heating to effect dehumidification in response to indications that the temperatures are nearing the dew point (86). Precise measurements of very low vapor pressure deficits, when relative humidity is greater than 90%, are particularly important. Under these conditions, the dew point is reached with a decrease in temperature of only a few degrees (85).

Horizontal air flow systems that use fans to move the air just above the crops at 12 m^3 per minute reduce the chance of reaching the dew point on plant surfaces during clear cold nights when heat is lost from plant surfaces by radiation (94, 95).

Most of the environmental management research has focused on *B. cinerea*, as this fungus affects such a wide range of ornamentals (156), as well as greenhouse vegetable crops. Although *Botrytis* has been reported to initiate infections using stigma exudate following dry conidial inoculation (169), controlling *Botrytis* is largely a matter of reducing free water on plant surfaces and lowering humidity. Foliar wetness can be managed with infrared heating systems, or irrigation systems that do not wet the foliage: trickle, drip, trough, and ebb/flood and flood floor irrigation (72).

Temperature affects but rarely limits Botrytis blight because the pathogen's effective range is so great: for gerbera, petal spotting was seen to occur over a temperature range of 4° to 25°C (135). Postharvest susceptibility of poinsettia bracts to *Botrytis* increased with increasing temperatures during production over a range of 16°–22°C, and was not affected by the use of DIF (night temperatures higher than day temperatures for the purpose of height control) (126); this effect may have been due to the advanced maturity of bracts on plants grown at a higher temperature. In gerbera petal spotting incidence increased at higher postharvest temperatures (89). Warmer temperatures also allowed greater disease incidence at shorter leaf wetness durations in geranium flowers (146). The higher radiation in greenhouses in spring and summer and consequent reduction of conidial infectivity apparently outweigh the disease-conducive effects of warmer temperatures in those seasons (89).

Use of long-wave infrared-absorbing plastic film for greenhouse covering reduces nighttime heat loss and thus the opportunity for condensation on plant surfaces, reducing Botrytis disease on tomatoes (160). Films that restrict UV light penetration also reduce Botrytis sporulation (130).

Wider space between plants improves air movement and also increases the exposure of lower leaves to light, thus reducing premature senescence and the accompanying Botrytis sporulation (72). Heated air forced up through the canopy of geranium stock plants (72) reduces inoculum production. By reducing relative humidity to less than 60% for at least 24 h just after cutting harvest, producers of geranium cuttings can reduce Botrytis stem blight, even when conditions more favorable to infection follow (71).

Powdery mildew in rose (*Podosphaera pannosa* f. sp. *rosae*) is another ornamental disease system for which there is extensive knowledge of environmental influences. The environment outside the greenhouse has a significant influence (144). Epidemics within a Colorado greenhouse began when outdoor dew points rose in early spring, and continued through the summer (36). Powdery mildew severity was reduced by halting evaporative pad cooling at sunset and thus increasing vapor pressure deficit. Heating was needed for disease control during the winter, when outdoor dew points were low.

Water sprays have been observed to reduce growth of colonies of mildew on roses (122, 172); outdoors, rain reduces sporulation for several days (147). The greatest inhibition was seen with water sprays 6–8 h after inoculation (122). Minute films of water may actually be necessary for rose infection, however (173). Studies by De Long & Powell (47, 125) indicated that a nighttime 12 h-dew period maximized powdery mildew infection in roses, and that shorter dew periods reduced disease. Extremes of moisture, either too high or too low, were detrimental to conidial germination. Moisture on the plant surface has also been found to be important for powdery mildew of begonia (127) and for powdery mildew on poinsettia (29).

Temperature can be a limiting factor for some powdery mildew diseases. Colonies on begonia were eradicated by a 6-day exposure to 32°C (127). Temperatures 30°C or higher halt epidemics for powdery mildew on poinsettia (25, 27). Symptoms of powdery mildew on poinsettia are suppressed by summer greenhouse temperatures (90).

Cultural Control

Practices that reduce initial inoculum in the crop or lower infection rate will result in a higher percentage of disease-free plants. The floriculture and nursery industries have used cultural innovations and technology to improve crop health.

SOILLESS MIXES The most important innovation in the culture of greenhouse and nursery crops was the adoption of soilless potting mix. In the 1940s a new soil mix concept was developed by horticulturists and plant pathologists at the University of California (6). These U.C. soil mixes used various proportions of fine sand

and sphagnum peat moss and avoided the use of topsoil, a source of soilborne plant pathogens. The floriculture industry continues to use soilless mixes based on sphagnum peat moss, but the fine sand has been replaced by other inert ingredients (e.g., perlite, vermiculite, or bark ash). The nursery industry has adopted soilless mixes based on pine or fir barks (75) because the cost of peat moss has become prohibitive at the scale of nursery production. Composted pinebark-based mixes have the advantage of a natural suppressiveness (76, 149, 150) against *Pythium* and *Phytophthora* spp.

WATER MANAGEMENT IN GREENHOUSES AND NURSERIES Application of irrigation water is a critical production practice: Too much water may favor many pathogens, too little water may predispose crops to opportunistic pathogens, whereas neither situation is optimal for plant growth. The normally resistant rhododendron cultivar 'Caroline' was predisposed to infection by *P. cinnamomi*, either by 48 h of potting mix saturation or by drought stress (22). The canker-causing fungus *Botryosphaeria dothidea* infects stems or leaves when free water is present, but dieback does not occur unless the plant is exposed to a drought stress (139). To combat bacterial leaf spot (*Ps. cichorii*) in chrysanthemum, the only cost-effective procedure was irrigation with buried drip tape to reduce foliar wetness as well as the use of a roof covering rather than a porous saran cover (20).

FERTILITY AND pH MANAGEMENT Because plant nutrients normally present in agricultural soils must be supplemented in soilless mixes, nutrients may in some cases be adjusted to suppress disease, such as by adjusting the level or form of nitrogen (81). An integrated system for *Fusarium* wilt management was developed for chrysanthemum (87, 171) that used nitrate-nitrogen and elevated pH. Excessive nitrogen has been shown to favor Botrytis blight (84), Phytophthora blight on rhododendron (78), and Pythium root rot in poinsettia (58). A 1:3 ratio of nitrate-nitrogen to ammonium-nitrogen in pansy suppressed *T. basicola* (39).

Management of pH can be used to suppress soilborne pathogens such as *Phytophthora* and *Thielaviopsis*. Rhododendron 'Boule de Neige' grown at pH 3.4–3.7 did not develop Phytophthora root rot, whereas disease was severe on plants grown at pH 5.8–6.0 (21). Maintaining soil mixes at a pH at 5.0 was a traditional cultural practice to control black root rot in poinsettia caused by *T. basicola.* At pH less than 5, trivalent aluminum (Al^{3+}) predominates in soil solution and can be toxic to spore germination and hyphal growth in *T. basicola* (106, 107). Drenches of aluminum sulfate to provide Al^{3+} to a soilless potting mix suppressed root rot of vinca (*Catharanthus roseus*) caused by *P. parasitica*; as pH was increased, increasing concentrations of aluminum sulfate were required for suppression (12, 13).

Biocontrol

Many opportunities exist for use of biocontrol in greenhouses (121). Botrytis blight caused by *B. cinerea* is a particularly difficult disease to control in many ornamental crops. The competitive saprophytes *Clonostachys rosea* and *Ulocladium atrum* have been evaluated with some success for suppression of *B. cinerea* on cyclamen (92), geranium (57), and rose (113, 174, 175). Necrotic tissue in the plant canopy serves as a site for Botrytis sporulation. As highly competitive saprophytic colonizers, *C. rosea* and *U. atrum* outcompete Botrytis for possession of the necrotic substrate (93). In potted mini-rose grown under high disease pressure, use of *U. atrum* at three production stages consistently resulted in less disease and less sporulation of Botrytis than on untreated plants and was better than or equal to the fungicide iprodione (174).

Integrated use of biocontrol agents and fungicides has proven useful in reducing the number of fungicide applications to a crop. For instance, Botrytis control in nonheated greenhouse vegetable crops was achieved using fungicide or the biocontrol agent, *Trichoderma harzanium* T39, with the choice of material dependent upon measured environmental parameters (144). We expect more examples of the integration of biocontrol agents, chemicals, and disease forecasting in the future for greenhouse and nursery disease management.

PERFORMANCE OF COMMERCIAL BIOCONTROL PRODUCTS Fravel has reviewed several products based on specific biocontrol agents that have been introduced for control of diseases on ornamental crops in both the greenhouse and nursery (56). Many of the commercial biocontrol products on the market have received extensive evaluation in university trials in which inoculum of the test pathogen was introduced or occurred naturally. Performance of biocontrol agents in many of these trials has been poor, with only 12 successful results in 54 evaluations taken from reports in *B&C Tests* and *Fungicide and Nematicide Tests* (*F&N Tests*) (Table 1). One of the most widely tested biologicals, *Trichoderma harizanum* T-22 (Rootshield and PlantShield), was ineffective in a number of trials when used against Pythium and Rhizoctonia root rot, whereas three trials showed benefit of this a. i. against Cylindrocladium, Pythium, or Rhizoctonia root rots (Table 1). In other trials with *T. harizanum* T-22 reported elsewhere, this biocontrol agent has led to improved crop growth and has been successful in control of both Pythium and Rhizoctonia root rot and powdery mildew on several ornamentals (64). *Trichoderma virens* GL21 (=*Gliocladium virens*), commercialized as SoilGard (and earlier, GlioGard), only controlled Rhizoctonia root rot in two of eight trials (Table 1) even though it was quite effective against both Pythium and Rhizoctonia damping-off in extensive development studies (104). *Bacillus subtilis* QRD 713 was the most successful biocontrol agent tested; four of seven trials with Serenade (now Rhapsody) controlled foliar pathogens, although strains GB03 and MBI600 of *B. subtilis* were ineffective as Companion and Subtilex, respectively, against several root pathogens (Table 1).

The poor performance of commercial products of biocontrol agents reported by university researchers (Table 1) may be due to several factors. These could include (*a*) an overwhelming amount of introduced inoculum that exceeds the inoculum density of the pathogen as it might naturally occur in production, (*b*) an

TABLE 1 Biocontrol of soilborne and foliar pathogens attacking ornamental crops with commercial biocontrol products[a]

Biocontrol product/agent	**Disease**	**Pathogen**	**Host**	**Disease control[b]**	**Reference**
AQ-10 biofungicide					
Ampelomyces quisqualis	Powdery mildew	*Oidium* sp.	Poinsettia	No	(66)
Companion					
Bacillus subtilis GB03	Pythium root rot	*P. aphanidermatum*	Geranium	No	(43)
	Rhizoctonia root and crown rot	*R. solani*	Vinca	No	(53)
	Fusarium corm rot	*F. oxysporum*	Gladiolus	No	(55)
Deny					
Burkholderia cepacia Wisc.	Fusarium corm rot	*F. oxysporum*	Gladiolus	No	(55)
Mycostop					
Streptomyces griseoviridis K61	Botrytis blight	*B. cinerea*	Geranium	No	(68)
	Black root rot	*Thielaviopsis basicola*	Pansy	No	(17)
	Fusarium corm rot	*F. oxysporum*	Gladiolus	No	(55)
	Phytophthora root rot	*P. nicotianae*	Snapdragon	No	(67)
	Pythium root rot	*P. aphanidermatum*	Geranium	No	(165)
PlantShield					
Trichoderma harzianum	Pythium root rot	*P. aphanidermatum*	Geranium	No	(43)
KRL-AG2	Rhizoctonia root and crown rot	*R. solani*	Vinca	No	(53)
	Phytophthora root rot	*P. nicotianae*	Snapdragon	No	(67)
	Pythium root rot	*P. myriotylum*	Caladium	No	(55)
Primastop					
Gliocladium catenulatum	Rhizoctonia root and crown rot	*R. solani*	Vinca	Yes	(53)
	Black root rot	*Thielaviopsis basicola*	Pansy	No	(17)

	Phytophthora root rot	*P. nicotianae*	Snapdragon	No	(67)
	Pythium root rot	*P. aphanidermatum*	Geranium	No	(165)
Rootshield					
Trichoderma harzianum KRL-AG2	Cylindrocladium root and collar rot	*C. pauciramosum*	Myrtle-leaf milkwort	Yes	(124)
	Fusarium corm rot	*F. oxysporum*	Gladiolus	No	(55)
	Pythium root rot	*P. aphanidermatum*	Geranium	No	(165)
	Pythium root rot	*P. aphanidermatum*	Geranium	Yes	(165)
	Pythium root rot	*P. ultimum*	Geranium	No	(108)
	Pythium root rot	*P. aphanidermatum*	Geranium	No	(108)
	Pythium root rot	*P. irregulare*	Geranium	No	(108)
	Pythium root rot	*P. ultimum*	Geranium	Yes	(109)
	Rhizoctonia root rot	*R. solani*	New Guinea impatiens	No	(52)
	Rhizoctonia root rot	*R. solani*	Impatiens	No	(167)
	Rhizoctonia root rot	*R. solani*	Begonia	No	(167)
	Rhizoctonia root rot	*R. solani*	Petunia	No	(167)
	Rhizoctonia root rot	*R. solani*	Vinca	No	(167)
	Rhizoctonia root rot	*R. solani*	Vinca	No	(54)
Serenade					
Bacillus subtilis QRD 713	Pythium root rot	*P. aphanidermatum*	Geranium	Yes	(43)
	Botrytis blight	*B. cinerea*	Geranium	No	(68)
	Powdery mildew	*Oidium* sp.	Poinsettia	No	(66)
	Alternaria leaf spot	*A. tagetica*	Marigold	Yes	
	Powdery mildew	*Erysiphe polygoni*	Hydrangea	Yes	(63)
	Cercospora leaf spot	*C. viola*	Pansy	Yes	(61)
	Alternaria leaf spot	*A. tagetica*	Marigold	No	(62)

(*Continued*)

TABLE 1 (*Continued*)

Biocontrol product/agent	Disease	Pathogen	Host	Disease control[b]	Reference
SoilGard					
Trichoderma virens GL21	Pythium root rot	*P. aphanidermatum*	Geranium	No	(43)
	Rhizoctonia root and crown rot	*R. solani*	Vinca	Yes	(53)
	Fusarium corm rot	*F. oxysporum*	Gladiolus	No	(55)
	Pythium root rot	*P. aphanidermatum*	Poinsettia	No	(16)
	Rhizoctonia root rot	*R. solani*	New Guinea impatiens	Yes	(52)
	Rhizoctonia root rot	*R. solani*	Impatiens	No	(167)
	Rhizoctonia root rot	*R. solani*	Begonia	No	(167)
	Rhizoctonia root rot	*R. solani*	Petunia	No	(167)
	Rhizoctonia root rot	*R. solani*	Vinca	No	(167)
	Rhizoctonia root rot	*R. solani*	Poinsettia	No	(54)
	Rhizoctonia root rot	*R. solani*	Zinnia	No	(161)
Subtilex					
Bacillus subtilis MBI 600	Black root rot	*Thielaviopsis basicola*	Pansy	No	(17)
	Fusarium corm rot	*F. oxysporum*	Gladiolus	No	(55)

[a] As reported in *Biological and Cultural Tests for Control of Plant Diseases*, 1997–2004 and in *Fungicide and Nematicide Tests*, 2000–2004, published by Am. Phytopathol. Soc., St. Paul, MN

[b] Disease control is noted as "yes" where disease development in treatments with biocontol agents was significantly less than the inoculated untreated control and "no" when no significant difference was found.

environment unfavorable for the biocontrol organism, and (*c*) an environment too favorable for pathogen germination and infection, in which the biocontrol agent cannot compete.

Although biocontrol agents at times perform equivalently to fungicides in comparative tests, biocontrol does not appear to be a stand-alone practical control measure for disease. Biocontrol agents are likely to perform best when pathogen populations are low or when coupled with naturally suppressive potting mixes. Thus, growers who improve sanitation and cultural practices will see greater benefits from biocontrol agents and be able to reduce the amount of pesticide used in crop production

Detection and Diagnosis

Scouting and correct identification of a disease problem is paramount for effective disease management in floriculture and nursery crops. Daily inspection of the crop is the best way to detect problems promptly. Head growers often have this responsibility, but some businesses have formal scouting programs. After detection, correct diagnosis of the specific problem is the second step. Some large facilities have an in-house pathologist, but in most cases samples are sent off to a diagnostic lab at a land-grant university. Diagnosis may be done by traditional and/or molecular methods. Identification of the pathogen is critical for determining which fungicide or bactericide is appropriate. Likewise, pathogen identification is needed to decide how to modify cultural or environmental conditions to suppress further disease development. The identification of the host-pathosystem also sometimes indicates where the pathogen might have entered the production cycle, particularly for seedborne pathogens or pathogens usually introduced via vegetatively propagated stock.

Chemical Controls

Fungicides continue to have an integral role in ornamentals disease management. Fungicides are rarely used alone, but typically are one component of an IPM program. Pieters (123) concluded that management of rose powdery mildew in the greenhouse could not be accomplished by environmental manipulations alone; disease monitoring of the number of leaflets infected was used to strategically time chemical inputs and thus reduce the total number of sprays needed. The Fusarium wilt control system designed by Woltz & Engelhard (87, 171) incorporated drenches with benomyl in addition to nutritional controls.

The effectiveness of new phosphorous acid products and others for Phytophthora and downy mildew control, and other broad-spectrum materials and reduced risk products for ornamental diseases were summarized recently by Chase (31). Three new active ingredients, cyazofamid, fenamidone, and pyraclostrobin, are anticipated to be registered in the United States for ornamentals use in the near future (33). Trial data to date suggest that pyraclostrobin has good effectiveness against powdery mildews, downy mildews, rusts, *Cercospora*, *Sphaceloma*, *Alternaria*, *Phytophthora*, and some effect on *Pythium* and *Rhizoctonia*. Cyazofamid and fenamidone trials indicate good effectiveness against *Phytophthora* and downy mildews.

Owing to the small worldwide market size for greenhouse and nursery fungicides and the high cost of product introduction, new chemical control products are usually developed for agricultural uses and then trickle down to ornamental uses—especially if a turf label is also possible. The fungicides available for ornamentals use are similar to those available to the rest of agricultural production. Thirteen of the top 15 agricultural fungicides worldwide for 2003 (8) are registered for ornamentals use in the United States.

The need for new systemic downy mildew and Phytophthora controls in ornamentals (26), for example, was answered through product development targeting late blight of potato and downy mildew of grape. Recently, dimethomorph, cyazofamid, and fenamidone have been introduced for ornamentals use in the United States. Mefenoxam resistance (82, 97) occurs in *Phytophthora* strains affecting ornamentals, so a diverse supply of new chemical tools is important. Successful use of fungicides against diseases of ornamentals caused by *P. nicotianae*, *P. drechsleri*, and *P. cinnamomi* is reported in recent editions of *F&N Tests*.

Management of powdery mildew disease in ornamentals has also profited from the development of chemistry targeted at other globally important markets, such as control of powdery mildew on grapes and European wheat. Chemical controls for powdery mildew were reviewed by Coyier (40). Since that time, additional active ingredients have been made available for use or testing on powdery mildews of ornamentals, notably some additional demethylation inhibitors (DMIs), as well as the strobilurins azoxystrobin, kresoxim-methyl, pyraclostrobin, and trifloxystrobin. The DMI materials are valuable as systemic controls of some powdery mildews, but the spectre of resistance development is always a concern for both strobilurins and DMIs. Horst et al. described the benefits of bicarbonate and oil as biorational fungicides for powdery mildew and black spot of roses (80). Neem oil and petroleum oil are helpful against powdery mildew, but, similarly to bicarbonates, need to be used with care to avoid phytotoxicity. Soluble silicon treatments have been tried for powdery mildew control on greenhouse roses, but use on ornamentals is not widespread in the United States (10). Powdery mildew studies have recently been reported in *F&N Tests* for many woody and herbaceous ornamentals. Registered active ingredients showing effectiveness in these trials included copper, thiophanate-methyl, chlorothalonil, phosphorous acid materials, and piperalin, in addition to strobilurins, bicarbonates, oils, and DMIs.

Botrytis fungicides are generally first developed for use on grapes. Recent Botrytis control trials on poinsettia and geranium (reported in *F&N Tests*) have shown decreased disease incidence or severity in treatments with polyoxorim, fenhexamid, iprodione, pyraclostrobin, and chlorothalonil sprays. For effective Botrytis control, the timing of fungicide applications may be critical. Because geranium cuttings are exposed to extensive periods of leaf wetness during propagation, it is a good strategy for growers to apply *Botrytis*-controlling fungicides to the stock plants prior to taking cuttings (72).

Greenhouse populations of downy mildew, powdery mildew and *B. cinerea* are particularly prone to develop resistance. Strains of *B. cinerea* resistant to benzimidazole fungicides or partially resistant to dicarboximides have been documented in N. America (96, 112, 118, 176); this resistance has appeared in many ornamental crops worldwide. A PCR test can be used to test *Botrytis* isolates for benzimidazole resistance (103). Some of the newer chemistries in use in the ornamentals industry are also vulnerable to the development of resistant *Botrytis* populations. Because of the frequent exchange of plant material among greenhouse growers of ornamentals, the development of resistance in any major production facility will be quickly shared with the rest of the industry (69). The possibility of adding oils to fungicides for improved control of partially resistant populations of *Botrytis* (23) may be useful; however, phytotoxicity is a concern (69). Rotation of materials with different modes of action is more economical than tank mixes, and has been recommended (41). But others contend that fungicides applied alternately do not slow the buildup of resistance because treatments are so close together that there is no time for the resistant portion of the population to be significantly set back; tank mixtures have been examined as an alternative (69, 111). Development of resistance is of particular concern when it arises in a pathogen of quarantine significance, e.g., *Puccinia horiana*, agent of chrysanthemum white rust, for which resistance to fungicides in carboximide, triazole, and strobilurin classes has now been reported (37, 49). Resistance is also an important factor in the management of soilborne diseases. A high incidence of mefenoxam resistance has been documented in greenhouse populations of *Pythium* (110) and *Phytophthora* (82, 97).

For bacterial control, coppers, mancozeb products, or copper plus mancozeb products are generally used (30, 117). Copper and streptomycin resistance has been documented for *Pseudomonas syringae* on nursery shade trees (138) and copper resistance on New Guinea impatiens (38); resistance may hamper management of other diseases as well. A new formulation of *Bacillus subtilis* with broad effectiveness provides a rotational or tank-mix partner to use with copper against bacterial diseases (30).

The recent introduction of *Puccinia hemerocallidis*, daylily rust, into the United States showed the industry how rapidly a new pathogen can become distributed through normal retail channels and hobbyist exchanges (168). Following a first detection on *Hemerocallis* in the United States in 2000, by the end of the growing season in 2001 the disease had been reported from 22 states. Initial tests indicated that chlorothalonil, mancozeb, triadimefon, and azoxystrobin consistently reduced symptom infection (24). Studies on the control of rust fungi (114, 115) indicated that germination of urediniospores was almost entirely prevented by azoxystrobin, chlorothalonil, copper sulfate pentahydrate, mancozeb, and trifloxystrobin during in vitro screening. Less than one lesion per plant developed on geraniums inoculated with *Puccinia pelargonii-zonalis* previously sprayed with azoxystrobin, chlorothalonil, copper sulfate pentahydrate, or mancozeb. Other fungicides tested belonging to the benzimidazole, dicarboximide, hydroxyanilide, and DMI groups were fungistatic rather than fungicidal to urediniospores. Although fungistatic materials may protect plants well, the materials fungicidal to urediniospores are valuable for limiting the movement of rust fungi into new areas on nonsymptomatic plants. Such materials would be appropriately used prior to shipping out of areas where a disease is known to occur, and/or upon receipt of plants known to be coming from such an area.

Foliar nematode control is an example of a problem unique to ornamentals; many crops may be affected, including chrysanthemum, hosta, Japanese anemone, and buddleia. These pests were previously controlled by the insecticides oxamyl and aldicarb. As these registrations have been eliminated, the problem of foliar nematodes in vegetatively propagated, closely spaced, overhead-watered plants in nurseries has risen alarmingly. Rechcigl (129) had some success using chlorfenapyr treatments on Japanese anemone for the control of *Aphelenchoides fragariae*. Although there was not 100% control, it was felt that propagation by division following nematode number reduction would ultimately result in some plants entirely free from nematodes (thus clean stock). Warfield (163) tested chlorfenapyr on lantana and buddleia and observed significant foliar nematode suppression on both plants 6 weeks after the first treatment.

Known systemic acquired resistance (SAR) stimulating products are not being utilized by the ornamentals industry, but a number of products claim to increase host defenses by undefined means. The SAR-inducing acibenzolar-S-methyl (ASM) has been trialed on ornamentals, but results have been highly variable according to host: On delphinium and impatiens, Pseudomonas blight was controlled with ASM, but geraniums were harmed by the same rate (30). ASM also gave complete suppression of late blight caused by *Phytophthora infestans* on petunia, but not on tomato (9).

The risks and benefits of chemical application need to be weighed in each situation. In addition to the cost of chemical treatment, there are sometimes negative side effects of pesticide use: stress, resistance problems, interference with biocontrol, or an increase in diseases normally held in check by naturally occurring antagonistic microflora (19). Certain fungicide treatments on healthy plants may have a negative effect on plant growth, and possibly increase the length of time to bring the crop into flower (73). On the other hand, chemical controls are sometimes critically needed when the crop is grown under cultural stresses associated with faster crop production. The development of IPM programs that use the fewest possible fungicide applications has been somewhat hindered in ornamentals culture because the cost of an insurance application is outweighed by the high value of the crop that may be at risk from a pathogen.

CONCLUSION

Although diseases such as Southern bacterial wilt and *P. ramorum* blight/sudden oak death have taken a tragic economic toll on ornamental crops in the United States in recent years, the attention paid to them will bring about a leap forward in our knowledge. Sanitation practices, detection methods, communication, and regulatory procedures will all advance substantially, improving the ability of the ornamentals industry to prevent and respond to disease outbreaks in the future. Additional research is needed to support progress in the development of integrated environmental, cultural, biological, and chemical control techniques for management of diseases in the greenhouse and nursery. We anticipate continuing improvements in our ability to manage diseases. Progress will be achieved through the development and application of host resistance, cultural, environmental, and biological methods of disease management, as well as through the use of effective chemical tools that present minimal environmental risk to nontarget organisms.

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